AN INVESTIGATION OF CREEP IN IRRADIATED POLYETHYLENE PLASTIC

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by

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ABSTRACT

Creep in metals and several of the more rigid organic plastics has been thoroughly investigated and fully described in the **literature.** However, creep in irradiated polyethylene plastic is a relatively new field awaiting experimental investigation. Therefore, a search for available information and an investigation into the methods of obtaining satisfactory reproducible data was conducted. Information on the meaning of creep and how it affects plastics is presented first. The necessary parameters and the information desired are discussed next. A description of the equipment constructed and used in the preliminary tests is given in the body of the report. Results obtained, their interpretation, and recommendations for future work are offered in the last part of the report.

The author wishes to express his appreciation for the assistance and encouragement given him by Professor Gilbert Ford Kinney of the U. S. Naval Postgraduate School in this endeavor.

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1. Introduction.

The scientific study of creep phenomena dates from 1905 when F. Phillips[1] published his results of observations on the slow stretch of india-rubber, glass, and metallic wire under constant load. He related the elongation of the material to the time load was applied by an empirical logarithmic equation. Although this work of Phillips was the first systematic study of the phenomena, the effect of materials under load and below their yield point was noticed by M. Vicat[2] as early as 1833.

Progressive work in this field was done by Andrade[3] in 1910 and 1914. However, it was not until 1919 when Chevenard[4] and Dickenson[5] published their experimental results and had the effect of making design engineers aware of the significance of this constant occurrence in materials under applied load. Prior to this time, it was customarily assumed by all designers that the metals had a definite breaking strength and that failure would not occur until an equal or excessive stress was applied. However, it was shown that failure will occur below the elastic limit when a significant load is applied and that the failure is dependent upon temperature and time.

While much work has been done on metals in regard to the phenomenon of creep, and many papers written on it, comparatively little has been done or written on this occurrence in plastics. With the tremendous increase in use of these organic polymers during and since World War II, it is quite necessary that more investigation be made. This is espe-

[1]Phillips, F., Phil. Mag. 9(1905) 513.

[2]M. Vicat, "Note Sur L'Allongement progressif du fil de fer soumis a diverses tensions", Annales de Chimie et de Physique, 54, 1833.

[3]Andrade, E. N. Proc. Roy. Soc. A 84 (1910).

[4]Chevenard, P., C.R. Acad. Sci. Paris 69 (1919) 712.

[5]Dickenson, J. H. S., Iron Steel Institute 106 (1922) 103.

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cially true in the last few years with the use of plastics as building materials on the increase.

Choice of a plastic to investigate was governed by the lack of data on this subject. Since only a small amount of data was published on polyethylene creep, this then was a logical choice. Irradiated polyethylene was picked from among the modified forms of the polymer since some knowledge of the effect of radiation upon the material is known. Open literature indicates that cross-linking is increased and made more uniform by the irradiation process. Some of the mechanical properties of this substance are listed in the literature and the vast difference between these properties in pure and irradiated polyethylene indicate a profound effect on creep of the modified polymer. Thus, the creep properties of irradiated polyethylene presented a virgin field for investigation and this thesis was initiated.

Military applications are numerous since both propellents and explosives are composed of plastic-type substances. Creep is a major problem where assembly procedures make it necessary to bond or otherwise fasten the plastic substance within a weapon. Stresses set up because of thermal expansion, fastening devices, etc., will cause creep and this may possibly cut down on effective shelf life of the weapon or, in the extreme case, may cause malfunctioning of the weapon.

An attempt to present enough background in creep properties to understand that which follows, and why special procedures are needed with plastics, will be given in this section.

To understand creep properties it is necessary to start with stresses and their effects on materials. Figure 1 shows a typical stress-strain diagram for metals and indicates several important points. First, that for truly elastic materials, stress is proportional to strain up to the

proportional or elastic limit (D) of the material. This is called Hooks Law and is shown as OD in Figure 1. The point E is called the yield point and is that point at which the material deforms rapidly with little or no increase in applied load. Above this point the deformation is more plastic than elastic. The ratio of the stress to the elastic strain is called Young's Modulus of elasticity for the material, and is a measure of its stiffness.

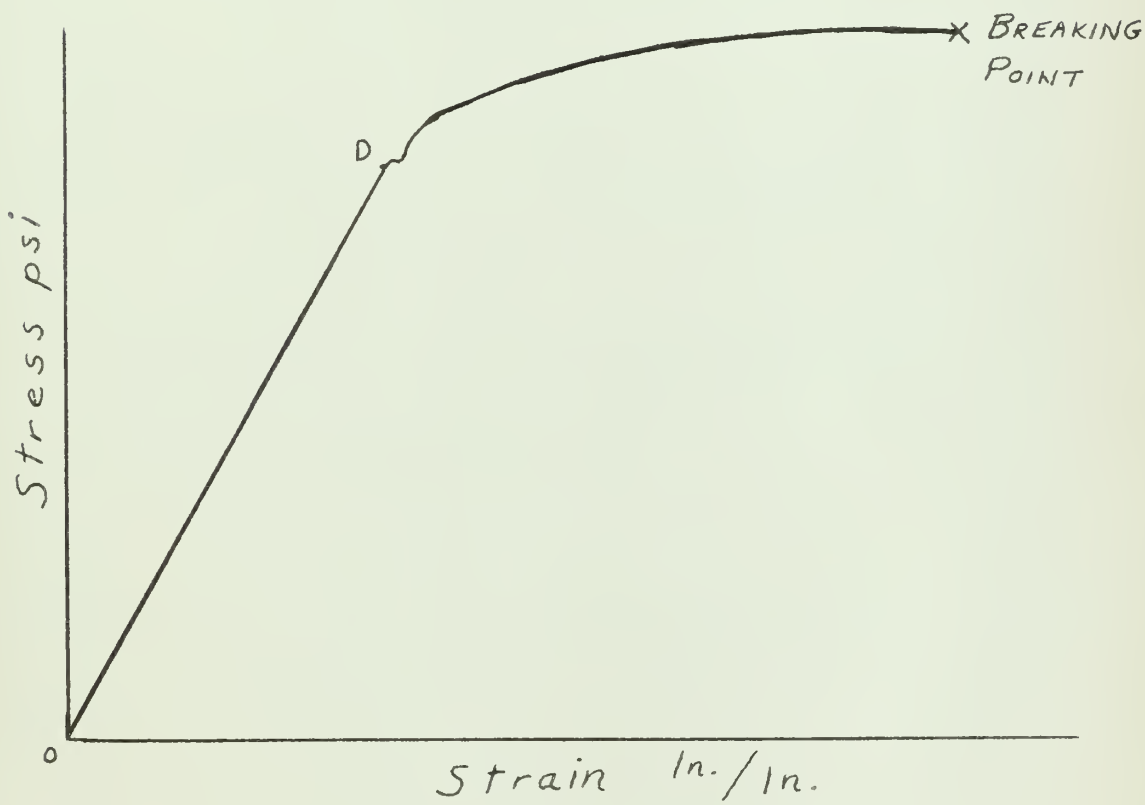

FIGURE 1: TYPICAL STRESS-STRAIN CURVE FOR METALS

Figure 2 shows a typical stress-strain diagram for the plastic to be used in this investigation and indicates a remarkedly different behavior than the material shown in Figure 1. Right at this point it would seem that since these basic mechanical properties are different in the two materials, that the creep would also be affected.

Another property of most materials indicates that strength decreases as the temperature increases. This is emphatically shown in Figure 3, which is a diagram of tensile strength plotted against temperature for polyethylene plastic.

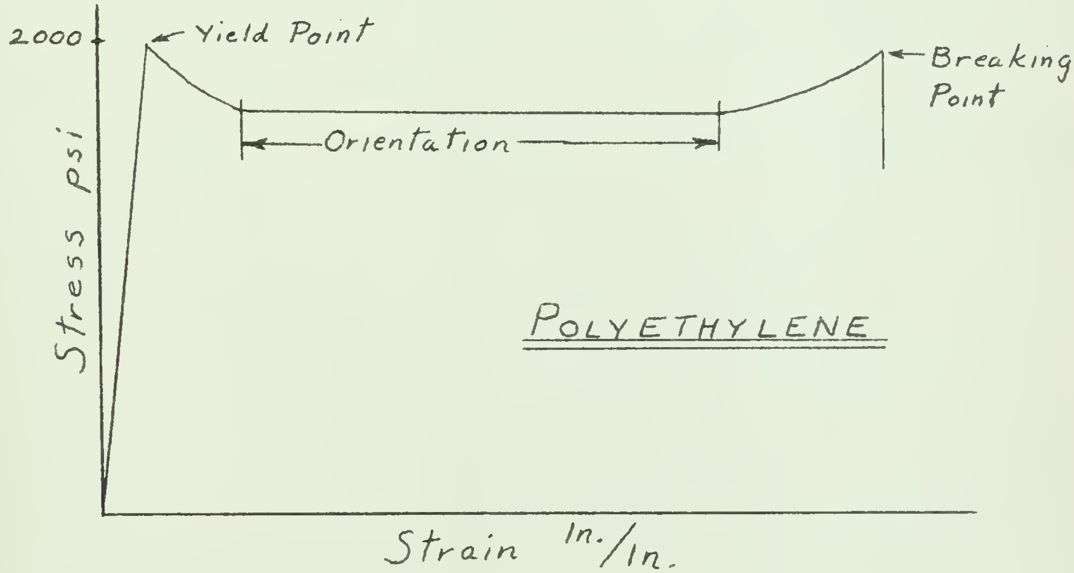

FIGURE 2

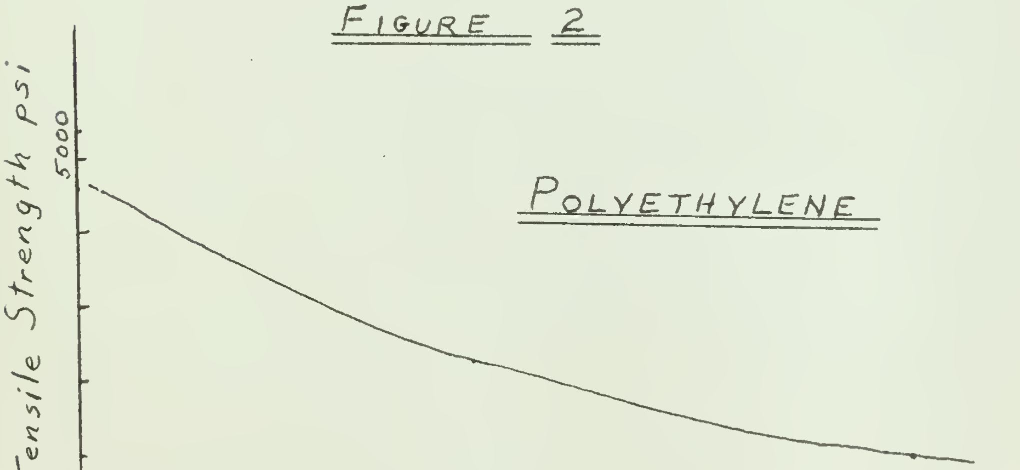

FIGURE 3

The phenomenon of creep has almost as many definitions in the literature as there are authors defining. Two definitions seem to be a good composite of all the others:

A: Creep may be defined as the time dependent deformation of a material under constant load or stress.

B: Plastic deformation or flow of materials held for long periods of time at stresses lower than normal yield strength.

Other pertinent definitions given at this time are:

Creep Strength[1] - the maximum stress which can be applied to material at a specified temperature without causing more than a specified increase in length in a specified time.

Creep Rate - rate of deformation. This is a function of load temperature and material.

An idealized creep curve is shown in Figure 4.

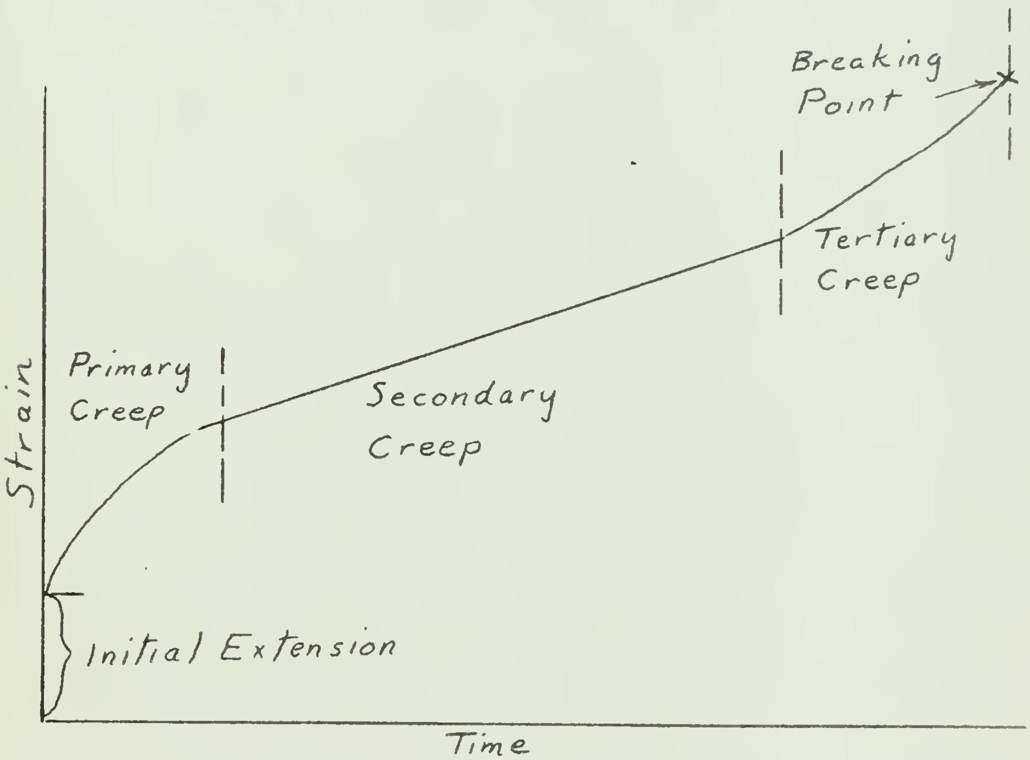

FIGURE 4 IDEALIZED CREEP CURVE

[1]For steel - 1% in $11\frac{1}{2}$ years.

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In this diagram are shown the various stages of creep which are as follows:

An initial extension (due to Hooks Law),

Primary creep - a stage at decelerating rate,

Secondary creep - a stage at almost constant rate, and

Tertiary creep - a stage at accelerating rate leading to failure curves of this type are available in the literature for metals and indicate to the design engineer the normal life expectancy of his finished product.

At this point are included two additional graphs, Figures 5 and 6, which show the effect of varying either stress or temperature and holding the other constant, upon similar material.

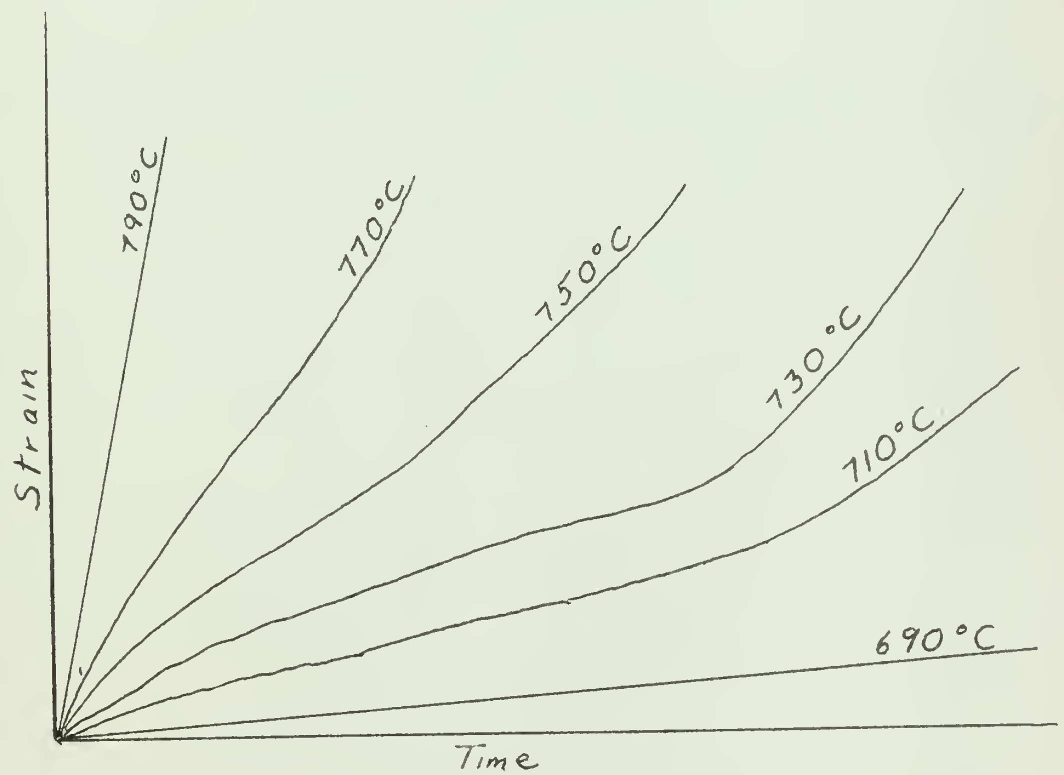

FIGURE 5: CREEP CURVES - CONSTANT STRESS

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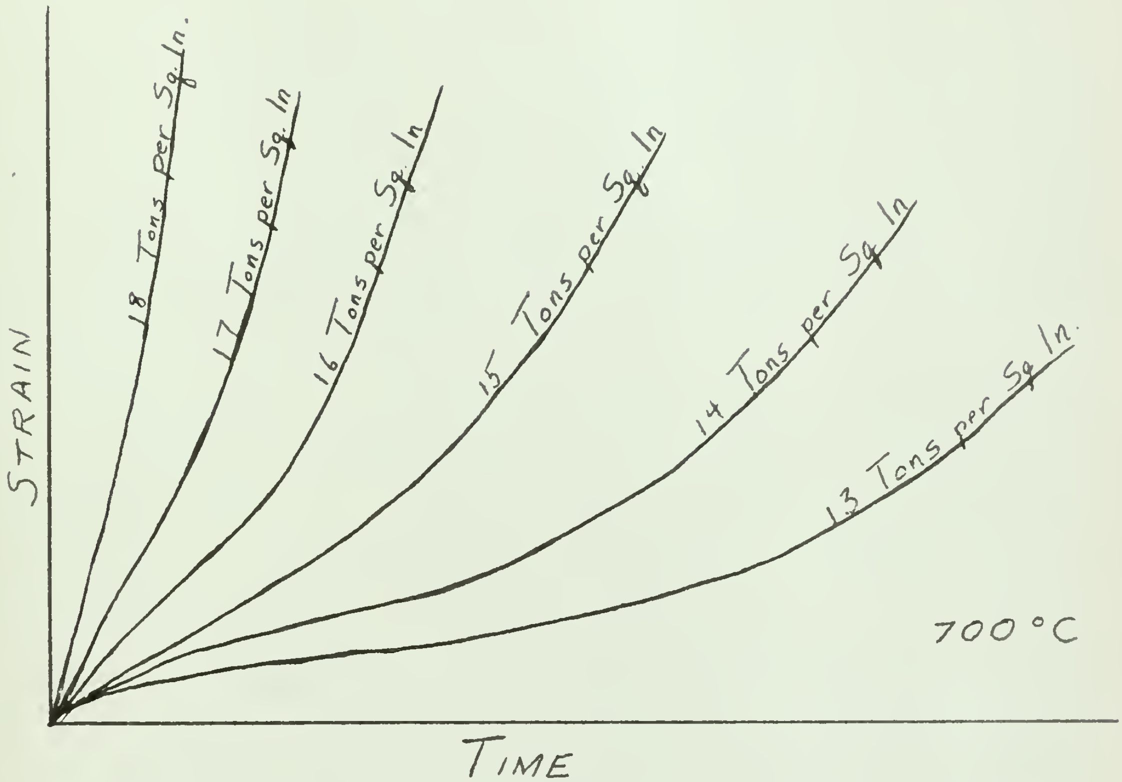


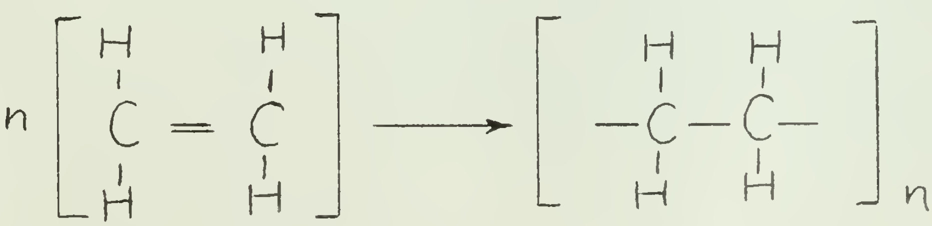
FIGURE 6: CREEP CURVES - CONSTANT TEMPERATURE

With this background we are now able to look further into creep in polyethylene plastic. Unlike metals (4) polyethylene of the compression molded type shows high elastic and plastic deformation during the first stages of creep, with the elastic component representing a high proportion of the total creep during this first period. As much as 78% of the total elongation is recoverable or we may say it is 78% anelastic. This is in good contrast to metals where little or no recovery is evident upon unloading.

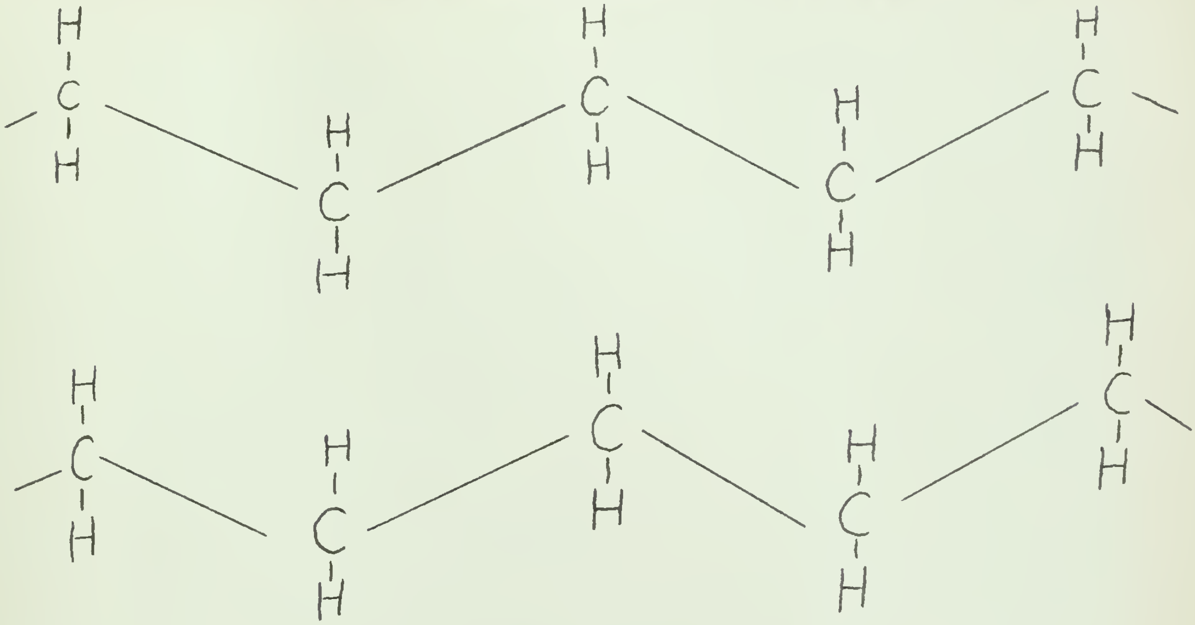
Creep testing in metals has been standardized and presents no special problem. Plastics, by contrast, have as yet no standardized procedure and the deviations from normal metallic properties as mentioned above, make it necessary to investigate new techniques. Preliminary work indicated that special load application and elongation measuring devices were necessary. Thus, a major portion of the investigation was to find a satisfactory method of determining and recording the necessary parameters. Once accomplished, necessary data could be gathered to determine the creep characteristics of the material chosen for investigation.

2. Polyethylene and Its Properties.

Ethylene has the formula C_2H_4 and is the raw material used in the synthesis of polyethylene. Various methods of polymerizing include heating and compressing ethylene in the presence of a catalyst, and polymerization by irradiation. The chemical equation for the process is relatively simple.

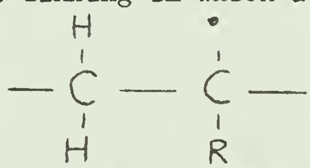


This process forms chains of random length and zig-zag in form.



The literature describes the plastic as partially crystalline and partially amorphous. Various groups of chains lying in a plane form what is known as a crystallite or two dimensional crystals.

The various chains are held together by the ordinary intermolecular forces, and also in irradiated material by the forces known as cross-links. This mechanism of cross-linking in which a radical stabilized by an R group, as shown,



is formed by loss of a hydrogen atom, which may then form a similar radical, R, on a nearby polymer chain. These radicals thus formed are in a favorable position to combine and only one primary ionization event is required to form a cross-link. Thus, the number of cross-links and their position partially determines the properties of the plastics.

The following table is included showing various properties of Polyethylene:

Table I (3) Polyethylene

Specific Gravity	0.92
Tensile Strength, p.s.i.	1,500
Elongation, per cent	120
Modulus of Elasticity, p.s.i.	19,000
Dielectric Constant, 60 to 10^8 cps	2.3
Dielectric Loss Factor 60 to 10^8 cps	0.001
Resistivity, ohm-cm	10^{15}
Dielectric Strength, volts/mil	420
Thermal Expansion, %/°F	0.01
Thermal Conductivity, Btu/(hr-°F-ft)	0.19
Specific Heat	0.55

The chemical properties of polyethylene are too numerous to list here, but they may be found in Chapter Six of Polyethylene by Raff and Allison (4).

3. Irradiated Polyethylene and Its Properties.

Irradiated Polyethylene is a modified polymer which has been exposed to radiation and thereby has had its cross-links increased. It is believed that the cross-links are spread more evenly throughout the matrix and, thus, the properties are vastly different from the pure polymer. The mechanism is essentially the same as described in the previous section, but is initiated by the high intensity irradiation.

General Electric produces one grade of irradiated polyethylene and calls it Irrathene 101. Since this material is the one to be used for actual test later on, its properties will be listed as typical of all the various irradiated polymers of ethylene.

Table II Typical Physical Properties of GE Irrathene 101 (4)

Tensile Strength, p.s.i.	1,800 - 2,200
Modulus of Elasticity, p.s.i.	18,000 - 20,000
Ultimate Elongation	500 - 600%
Hardness	R11
Specific Gravity	0.92
Water Absorption	Negligible
Flammability	Slow Burning
Chemical Resistance	Excellent to acids and alkalis
Solvent Resistance	Good below 60°C. Badly swollen by hydrocarbons and chlorinated compounds above 60 - 100°C.
Resistance to Sunlight	Must be protected from sunlight.
Dielectric Strength volts/mil	2,000
Dielectric Constant 60 to 10^3 cps	2.3
Insulation Resistance	Over 20 X 10^6 meg ohms

Additional properties are given in Chapter Six of Polyethylene by Raff and Allison (4).

4. Parameters and Methods of Testing Creep.

In general this section will include those parameters that affect the investigation, the possible methods of obtaining usable and reproducible creep data, and the desired results.

By the definition we see that creep is a function of temperature and time for any given load. The material and its previous history are also of prime importance since addition of modifying compounds, exposure to weather and sun, storage time and any previous work will affect the properties, both physical and chemical, of the material. By the very nature of

the investigation, it is of importance to reduce the number of parameters to as many as may be handled conveniently in the allotted time. It is also necessary to confine the parameters to the realm of measurements which may be taken without undue time consumption and extremely elaborate equipment. Thus, it is indicated that continuous readings be taken throughout the individual runs. By this method, also, a run may be in progress while a previous run is being analyzed. Each of the above-mentioned parameters will be studied separately to determine its usefulness and to determine whether or not it can be eliminated.

Temperature is an important function for several reasons. It is general knowledge and may be shown experimentally, that strength of a given material decreases rapidly with rise in temperature. This is nicely shown in Figure 3 which indicates the effect of increasing temperature on polyethylene. Another reason for considering temperature is the normal range that plastics are subjected to in everyday applications. This amounts to a range of about 30° C and since for most organic reactions, the rate of the reaction almost doubles for each ten degrees rise in temperature, it is reasonable to assume that the reaction rate of creep will increase also.

Load is paramount also since previous work in creep indicates that the creep rate increases with increase in initial loading. This is intuitive since most plastic materials subjected to stress will flow more easily as stress is increased. However, since we are interested mainly in the physical results of an investigation of this nature, and the maximum rate of deformation is useful, we can confine our load to the region near the yield point. By holding the load in this region and holding it constant during the run we effectively eliminate load as a parameter.

Time, on the other hand, must be retained as a parameter by the very nature of the endeavor.

The material and its previous history are variables which may be made constant by selection of one batch of product. However, a complete investigation into irradiated polyethylene indicates that a series of runs be made on plastic exposed to several dosages to determine the effect the various amounts have on creep. This was planned if a method of determining reproducible data were found. For the present, however, let us consider only one material with one modification and thus eliminate these parameters.

Holding all others constant we now have two variables, temperature and time, which must be accurately measured to give workable data.

In considering possible methods of organizing data on creep, two of these appeared to be reliable. The first method is to run many tests on the specimens while varying temperature and putting results in a graphical form for comparison. The data thus obtained might be related by an empirical equation with which new or untested ranges could be calculated.

A more elite method, and one that is apt to give more meaningful results, is to determine the activation energy of the reaction involving the creep phenomenon. This method was considered to be best and the intended procedure and desired results are as follows. First, a method of maintaining a constant load was to be found. Next, methods of finding the exact extension and of maintaining constant temperatures over a range of temperatures had to be planned. Time had to be recorded also. The desired result was a curve from which an energy of activation could be determined.

As indicated in Figure 7, such a curve can be plotted from the parameters chosen. The slope of this curve is related to these parameters by the equation:

$$\log \frac{\theta_1}{\theta_2} = \frac{\Delta H^*}{2.3R} \left(\frac{1}{T_1} - \frac{1}{T_2} \right)$$

Where: θ = time in seconds

ΔH^* = energy of activation

R = gas constant

T = absolute temperature

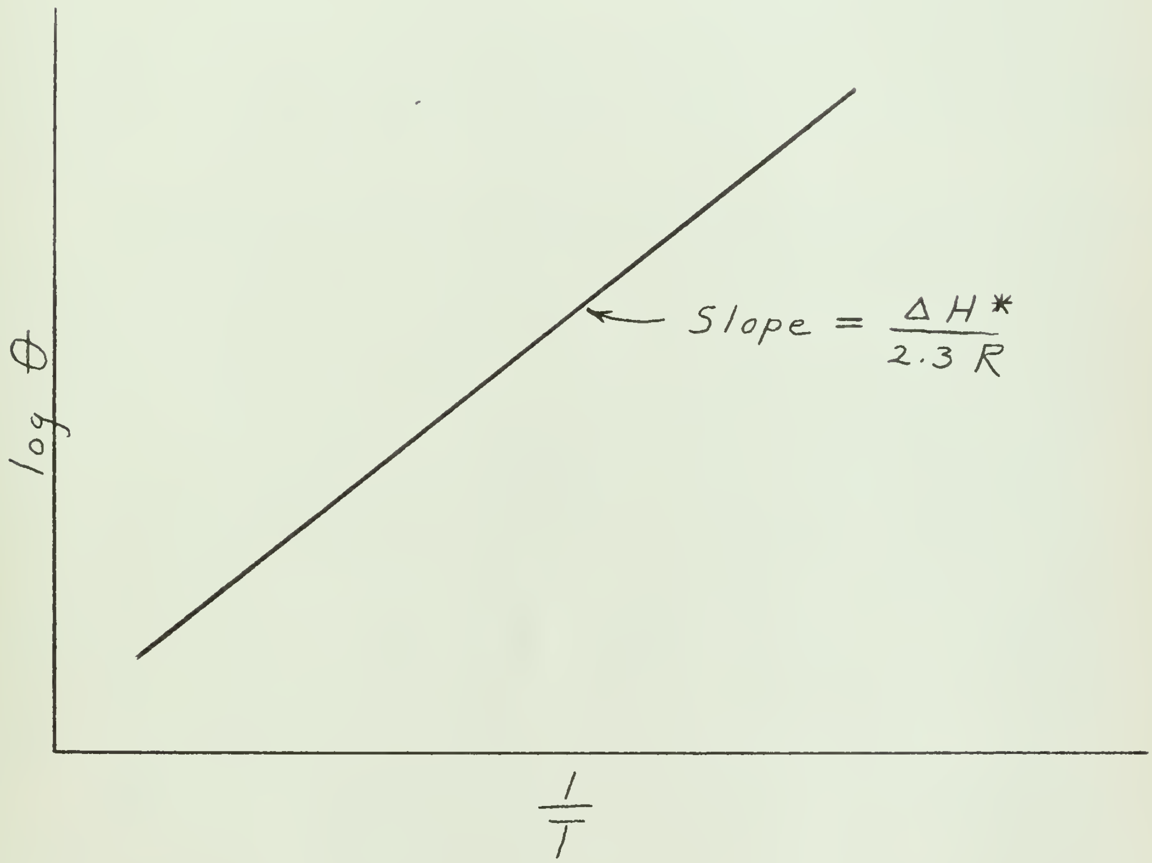


FIGURE 7: ENERGY OF ACTIVATION

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To congeal the various statements about testing creep, it is possible to say that the accurate assessment of creep properties depends upon three things which are nicely stated by Sully (5) and quoted here:

> It is important that special attention should be given to:
>
> 1. the design of the testing machine and the method of applying the load to the specimen,
>
> 2. the maintenance of the specimen at a constant temperature,
>
> 3. the precise measurement of the change of dimensions with time.

The testing machines usually used are of the type in which load is applied by means of a lever arm and the load is varied by shifting a weight along this lever. By suitable leveling devices the load may be kept constant.

Specimens for creep testing must be of sufficiently small dimensions to ensure no temperature gradient within the material when the ambient temperature is changed. Since the variation of creep properties with temperature is very large, it is necessary that the gradient along the specimen, as well as through the cross-section, be kept at an absolute minimum. Data derived when creep rates were different throughout the specimen would give erroneous results. Also, since the temperature has to be varied, it is imperative that the material reach equilibrium temperature conditions as soon as possible. Thus, a thin rectangular cross-section is indicated.

Control of temperature is of utmost importance and considering the length of time of these experiments, it is also difficult. Changes in current supplied to the heating device and changes in ambient temperature may produce fluctuations out of the realm of tolerance. Thus, considerable thought has been given to accurate control devices and these are commercially available. In metals the temperature of the metal may be measured,

but in plastics there is need to measure the bath temperature and rely on sufficient convection transfer of heat to maintain the proper temperature at the surface of the specimen.

Elongation measurement must be quite accurate to determine the creep properties. In metals where creep elongation is low, extremely accurate devices must be used. In plastics, which extend more readily, less accurate equipment may be used. Extensometers which electrically bias a recording instrument are the best type and may be used for continuous readings. There are, however, both mechanical and optical extensometers which are quite accurate but must be read directly.

The procedures and techniques for determining creep properties in metals are standardized and apply almost universally to metals. By contrast, plastics deviate from any set rule and the method of best determining creep must be planned for each individual plastic. The more rigid plastics, such as lucite, more closely resemble metal than do the less rigid plastics, such as polyethylene and polyvinyl chloride.

Failure in the more rigid materials is determined by an actual fracture of the specimen. On the other hand, materials such as polyethylene will sometimes stretch many times their original size before failure. Thus, in these cases it becomes necessary to define failure at some specified length. For our experiment we chose one graph width as the failure point.

5. Description of the Equipment.

The equipment to be used in this investigation was chosen for availability, application to techniques and standardization. It was hoped that this last item would be an aid to having results checked by other laboratories once the proper technique was established. Since plastics in general and particularly polyethylene do not conform to metals in the manner in

which they yield to stress, it was felt that the normal creep testing machines would not give the best results. Hence, different equipment was used in this experiment. For simplicity and in the hopes of reproducibility in other laboratories, as noted above, standard laboratory equipment was used whenever possible.

The major piece of equipment used for this investigation was the Riehle PS-5 Screw Power Universal Testing Machine with 5000 pounds capacity. The lower pulling head is powered by a variable speed reversible drive. The output of this drive is reduced through a two speed and worm reducer combination and this provides a wide range of speed control. The low range is used for testing while the high range is used mainly for adjusting head position.

The sensitive part of the loading unit, consisting of the table, compression rods, and upper head, forms a cage which is supported on a series of knife edges of a lever system which reduces the load to a fraction for weighing. The end of the lever system extends over to the indicating unit. Two types of grips are supplied, wedge type and Scott type, which is the type used since the wedge type cut the specimens. This latter type utilizes integral head grips to hold the Scott grips which hold the specimen. Over-travel limit switch protection is provided for both directions of head movement, as well as overload protection which is provided in the indicating unit.

The Riehle "Pendomatic" indicating unit houses the drive motor, weighing system, speed control, load pacer, and control buttons. The unit provides for pen recording of data and incorporates automatic load holding features at predetermined loads. The well known pendulum "dead weight" system for weighing is used throughout.

Extension of the test specimens was measured with a Model PS-8M Extensometer. This extensometer is designed for use with suitable autographic recorder equipment to obtain stress-strain diagrams covering the entire range of deformation of non-rigid plastic tension specimens. Strain magnification ratios of one-half, one and two to one are available on the recorder strain magnification selector. Thus, one inch of relative displacement of the gage grips is represented as two, one, or one-half inch on the recorder. An additional feature of this piece of equipment is the fact that it does not have to be removed from the specimen before fracture.

A constant temperature water bath manufactured by the Fisher Scientific Company was used as a temperature regulating source. It was chosen since it has control features within one-tenth of one degree and because the temperature may be varied easily by means of a screw control. This item was used with the temperature coils described below.

The temperature of the specimen was controlled by a coil of tubing surrounding the specimen and using air as a bath. The coil was surrounded by an insulated box to prevent heat loss and the entire unit was suspended from above and attached to the machine structure. This unit was built by the author and is shown in Figure 8.

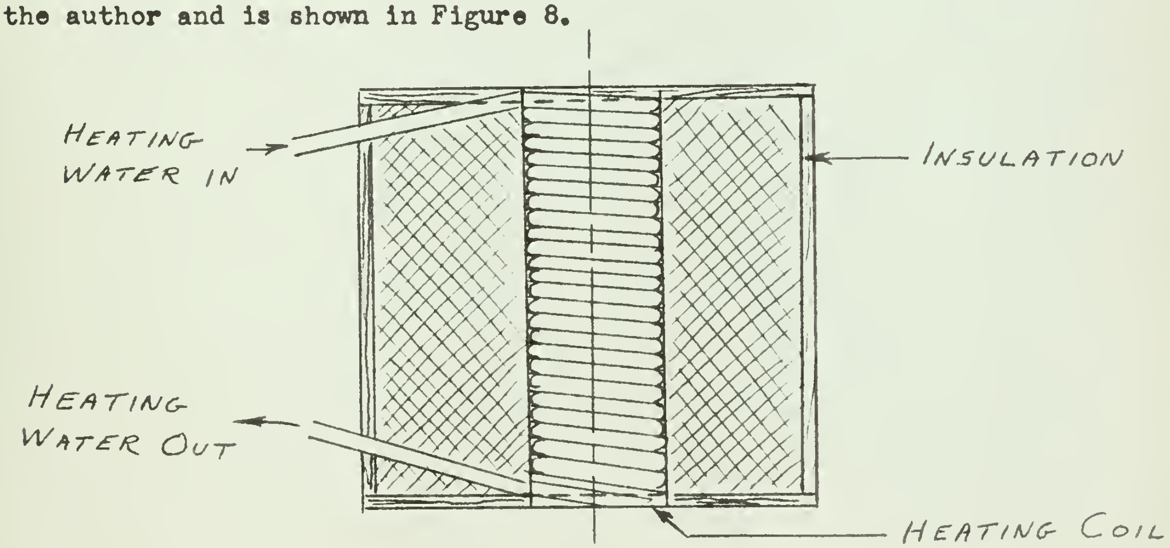

FIGURE 8: HEATER UNIT

The measuring circuit was the next major portion of the equipment. This, too, had to be manufactured and presented some problems since elongation and time were to be recorded simultaneously. The extensometer output drives a servo mechanism which in turn rotates a drum in the recording unit. The drum shaft was fitted with a gear which meshed with another gear of the same size to which a Giannini Universal Potentiometer was installed. This last was chosen because of accuracy and linearity. A circuit was manufactured with a small cell in series with a one meg-ohm potentiometer and circuit switch. Across this the universal potentiometer was placed and its variable lead was lead through a Leeds Northrup recorder and back into the circuit. By varying the one meg-ohm potentiometer, the total displacement of the Leeds Northrup recorder could be varied. Thus, by varying this potentiometer to cause the recorder to move the same distance as the grips of the extensometer, we were able to reproduce the extension on the recorder. At all times this could easily be checked since the pen recorder on the Riehle indicating unit recorded the total elongation of the specimen. The measuring circuit and a schematic of the measuring system are shown in Figures 9a and 9b. With this measuring circuit, the extension of the test specimen was transmitted directly to the Leeds Northrup recorder and since this device measures displacement and time, we now had a recording unit to measure elongation against the time the load was applied.

As stated above, the Riehle tester maintains constant load on the specimen. The operation of this is simple. Load is applied to the specimen and a constant load pointer is set at the predetermined level. When the indicating pointer touches the constant load pointer, the machine cuts out. As the specimen stretches, it indicates a lower load to the weighing system and the pointer is backed off to actuate the electrical end of the machine. Load is thereby applied again and the process repeats itself.

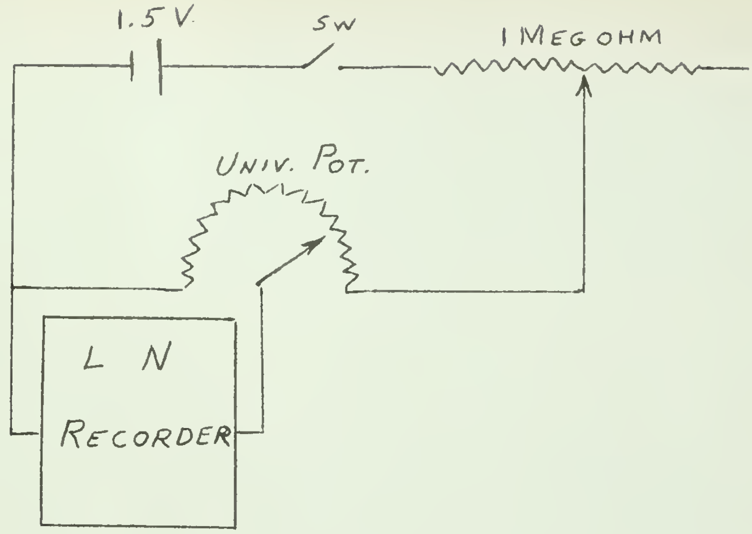

FIGURE 9a: MEASURING CIRCUIT - ELECTRICAL

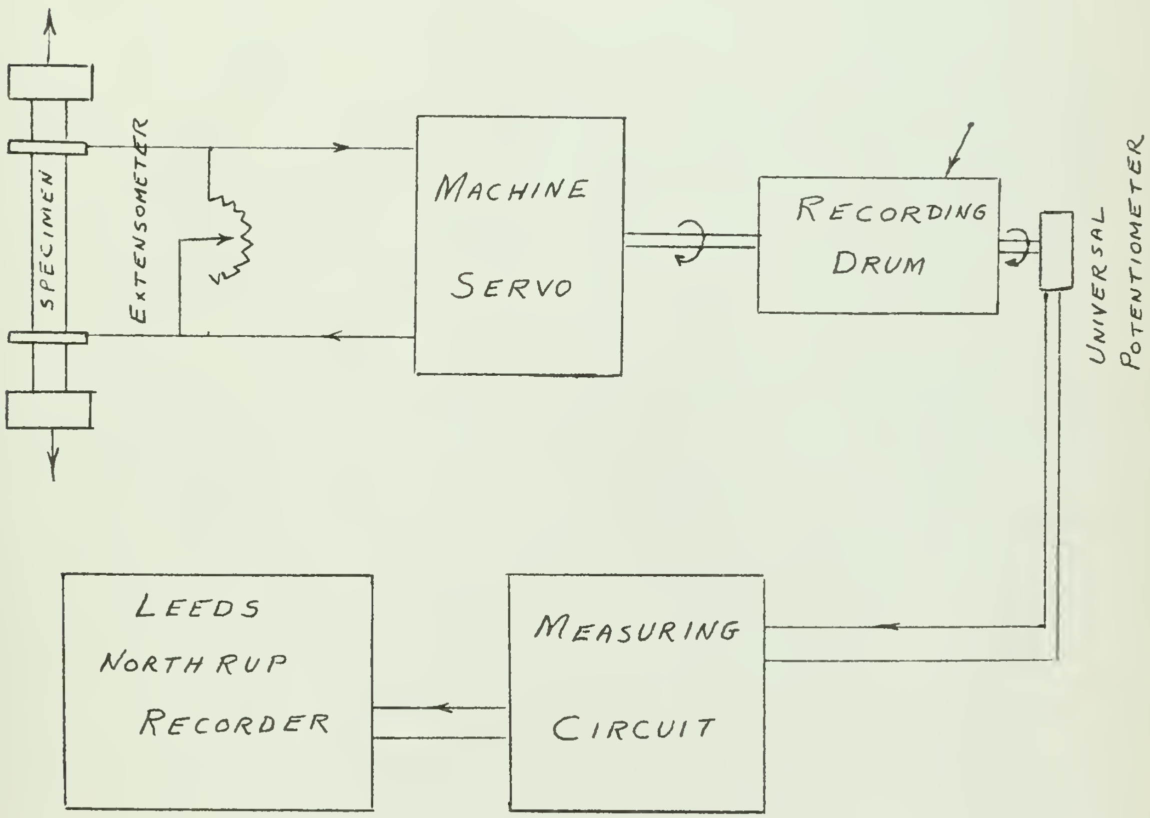

FIGURE 9b: MEASURING CIRCUIT - SCHEMATIC

At this point it may be stated that all the equipment mentioned above performed as designed. Some of the results were not as anticipated and since this is covered later on, it will not be covered here. However, it is felt that a major development in the investigation was accomplished by means of this equipment.

6. Experimental Procedure.

When the machinery was finally set up, the preparation of the specimens was the next important item. It was decided to use polyethylene to determine the best procedure rather than waste Irrathene 101 tape which is rather difficult to obtain in the desired dosage ratings. Therefore, tapes of unmodified polyethylene were cut from sheet stock with a thickness of .004 inches. Since the Irrathene 101 tapes were one inch by .005 inches, it was necessary to make the polyethylene tapes one and one-fourth inches wide. This way, we would be in the near vicinity of the Irrathene, when we switched to it, since we were using the same cross-sectional area of .005 inches.

In general, the stepwise procedure for running the experiment was decided upon only after six preliminary runs. To help in determining the best procedure, the author set up these first tests and varied such things as loading rate, temperature, load, and speed of recorder. The fastest loading rate was found to be best because it shortened the machine's recovery time. Temperatures in the vicinity of 30°C were the best for polyethylene since much above this point the specimens lose strength rapidly. Load was most critical since the machine was designed to be most accurate at mid-scale and we were operating at the lower end of the scale. The speed of the recorder was best set high for the initial part of the run and reduced to slow speed once creep was noted in the specimen. The slow rate of

the recorder was 32 minutes per inch. The fast rate was not timed since it was of no interest and the machine was set on fast for such a small amount of time in comparison to the time it was on slow rate.

The stepwise procedure that was derived from the above is given as follows:

1. Prepare specimen,
2. Energize water bath,
3. Energize testing machine and recording circuit,
4. Insert specimen in grips and wait for thermal equilibrium to set in,
5. Install extensometer grips,
6. Apply an initial load,
7. Zero testing machine and recording circuit against extensometer. Lock gear train on servo drive,
8. Apply load slowly to a point just below the yield point,
9. Move constant load pointer to cut off loading and lock it,
10. Allow machine to run until desired data is recorded,
11. Secure the machine and the recording circuit and remove records and specimen from the equipment,
12. Analyze data.

This procedure proved to be less time consuming than any other tried. Results of runs using this method are given in the next section.

7. Results.

Several runs were made using the equipment described above. The machine applying the load functioned well at first, but due to the nature of the material was subjected to abnormal starting loads. That is, it was forced to start so often to keep up with the load that it chattered and soon burned out the tubes in the internal control circuit. Once repaired,

however, it performed as designed. The nature of the resulting graphs indicated that a different method of applying the load is necessary. While negative, the results were good and indicated that a more steady loading device, such as a static weight, is a better method of accomplishing loading.

Negative results were also indicated in the heating device. As designed, the device formed a column of heated air and due to lower density of the heated air, acted as an air pump. Thus, ambient air temperature still had an effect on the material inside the coils. Another factor that was not good was the large elongation of the test specimen which removed some of the material from the vicinity of heated air. Thus, a larger heating cell, which would encompass the entire specimen and which is large enough to permit full extension of the material is indicated.

Positive results were obtained from the measuring circuit which performed exactly as designed and was heartening. Properly applied with a different loading device and heater, it will give the desired results.

Figures 10, 11 and 12 show typical results of the various runs. In Figure 10 is shown the effect of varying the load on the creep rate of the specimen. The load was increased from 3.5 pounds to 3.75 pounds near the middle of the run. The large increase in creep rate is indicative of the critical nature of the load applied. As noted from studying the curve, the creep rate never steadied down and we were still in the first stage or primary creep.

Figure 11 shows the effect of holding the load constant for approximately the same length of time as in the first run. A decreasing rate of creep was noticed first and then it apparently leveled off to what looks like secondary creep. However, this is not the case since the machine failed to operate over this period. Had secondary creep set in the line

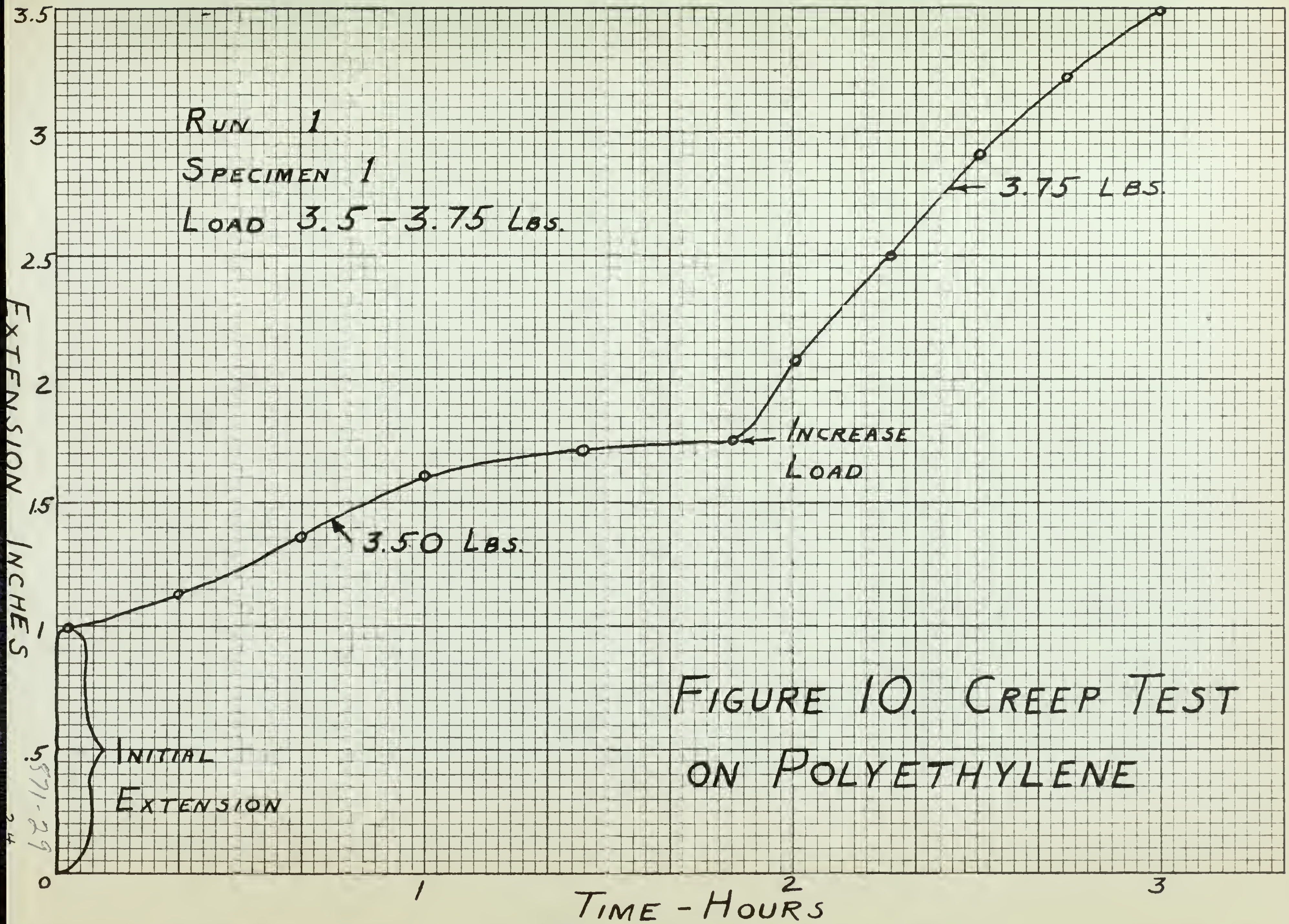

Figure 10. Creep Test on Polyethylene

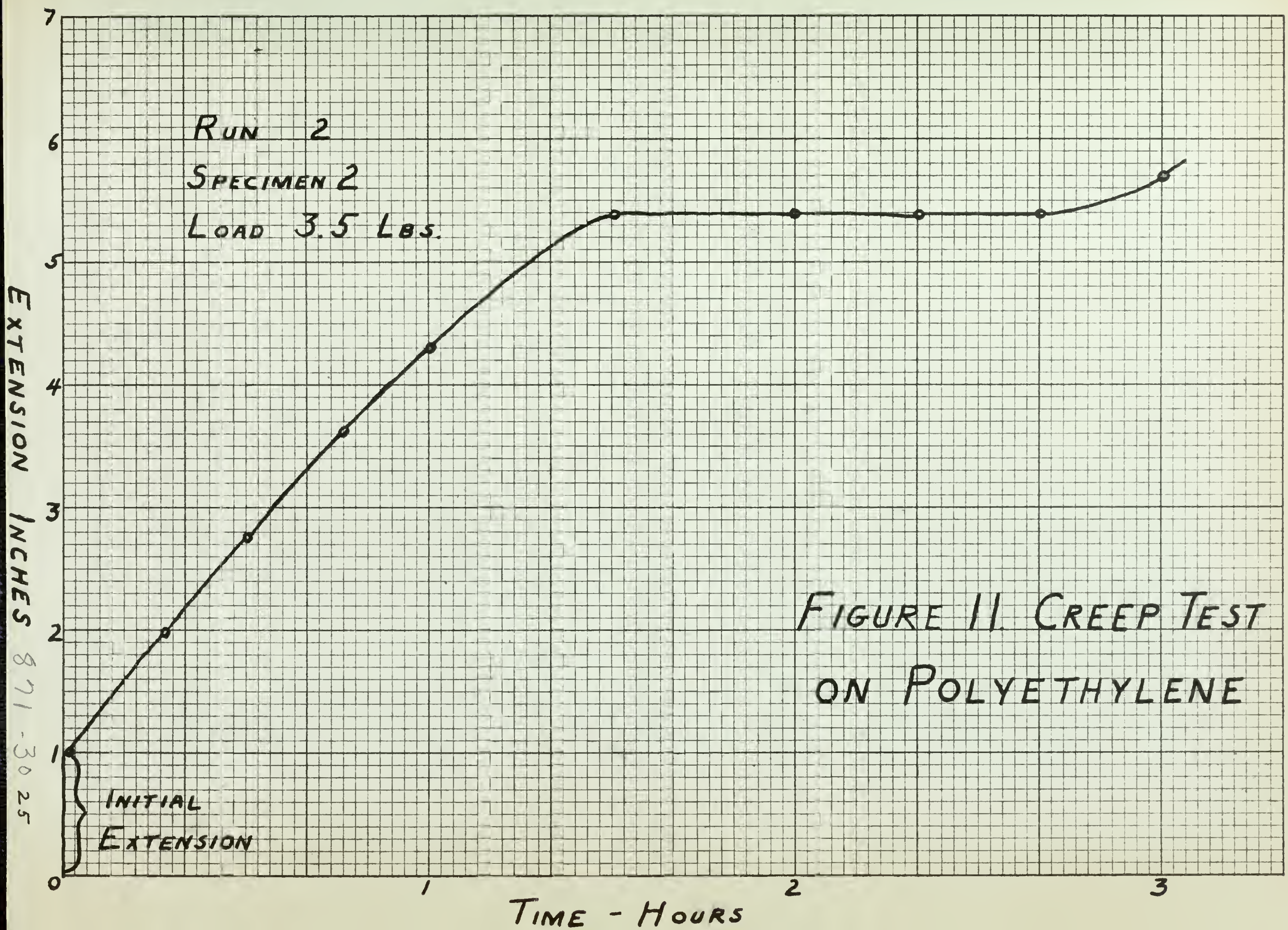

Figure 11. Creep Test on Polyethylene

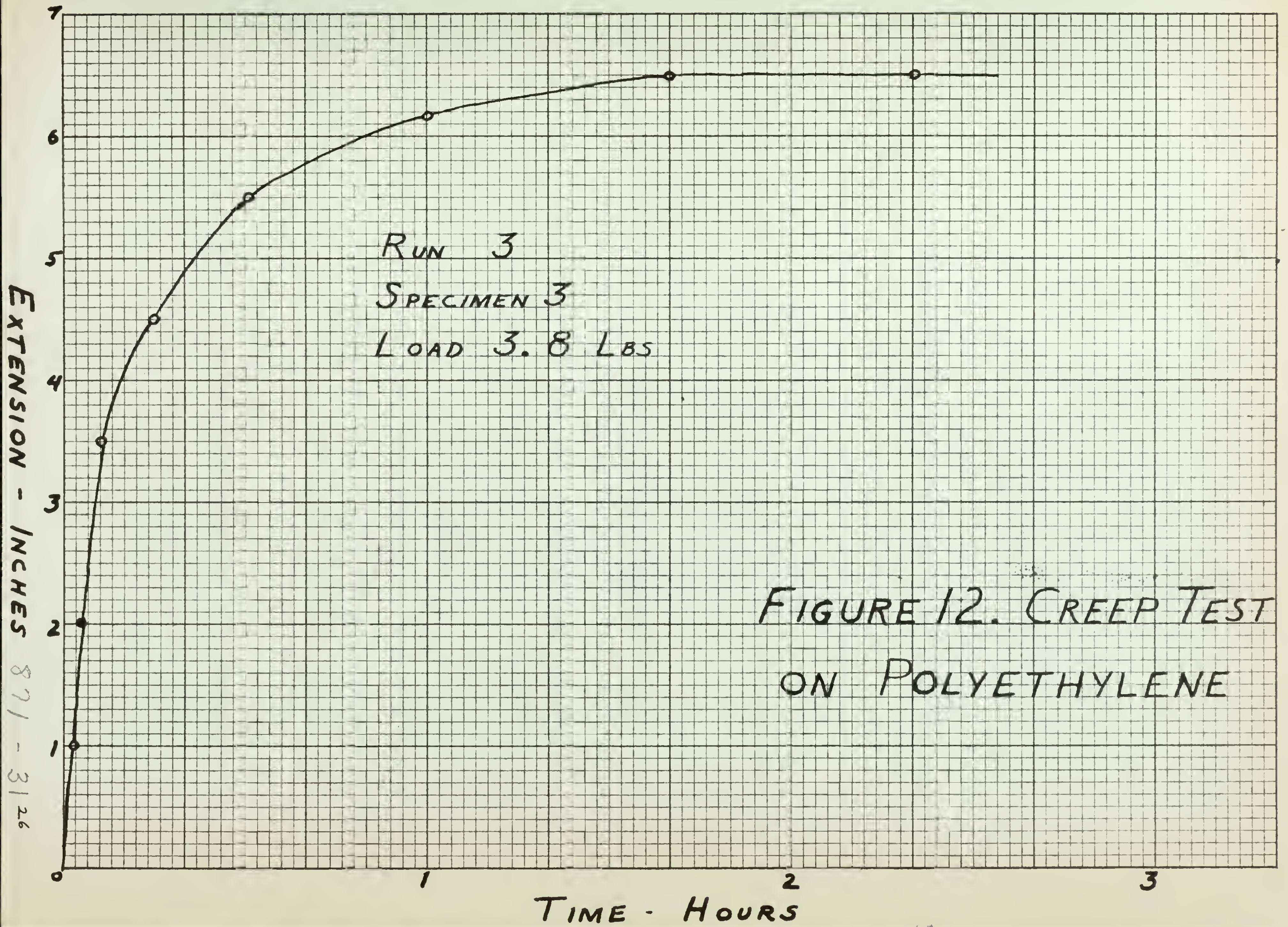

Figure 12. Creep Test on Polyethylene

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which is leveled off, it would have had a positive slope, since for secondary creep to occur the material being tested must elongate.

Figure 12 is typical of all the remaining runs performed. There is no apparent dip or jump to indicate where initial extension stops and creep begins. There is apparently a large elongation or stretching taking place along with the creep. This is a good run initially since this is what is expected and has been previously reported in the literature (4). As time progresses, it is quite certain that the machine failed to operate again since the curve leveled off once more as in the previous run.

As noted above, more runs were conducted and gave substantially the same type of curve as indicated in Figure 12. At this point, due to lack of time to build new equipment, it was decided to discontinue the experiments and analyze what had already been accomplished.

A summary of results:

a. Machinery not functioning properly - negative result.

b. Heater not sufficient to do the necessary job - negative result.

c. Measuring circuit operating perfectly - positive result.

It is felt that the negative results have the same significance as has the positive one. The person or persons who may continue with this work will be able to eliminate two pieces of malfunctioning equipment and substitute equipment that will give better results. The measuring circuit is a good piece of equipment and should be used in the next experiment involving creep.

8. Conclusions and Recommendations.

a. The experiment was not carried to completion since the machinery did not function as desired. It was felt that to continue and to test Irrathene with faulty equipment would have given erroneous results.

b. The use of the Riehle Testing Machine to apply the constant load is not good and should be eliminated from the test equipment. The machine, as designed, is a fine one but is applied wrongly for this experiment. Small tapes must be used for this work and at such low loads, the testing machine is not sufficiently accurate to give the fine difference in loading that will be a deciding factor in determining the creep rate of the material and ultimately, the activation energy of the creep process. It is, therefore, concluded and recommended that a static loading device be manufactured and used for this endeavor. The author recommends making a device that is similar to the Riehle Tester and installing it in front of the Riehle. By doing so the present extensometer can be used, as well as the present measuring device. The loading device should consist of a base and a rigid head supported by two round columns upon which a movable head may ride. The weight of the movable head and the extensometer should be counter-balanced by a pulley weight system to make them effectively weightless. Small positive weights may then be added to the movable head and will load the test specimen statically. With this system, minute changes are possible and the effects of the machine are removed.

c. The heater, as designed, was not sufficient to accomplish the fine temperature control so necessary in this investigation. A heater which will surround the entire testing machine is recommended for future work. A large box sitting on the deck and surrounding the whole machine will eliminate any effect of the ambient temperature. The material used for this box should be the insulating type such as beaver board. The heating may be done by coils along the sides of the box or by means of electric light bulbs. The temperature control unit should be placed inside this box to eliminate any drop in temperature due to convection. A small circulating

fan could be employed advantageously to prevent "hot-spots" and ensure constant temperature throughout the box. The use of a liquid bath is not feasible with the present extensometer nor is it recommended.

d. The measuring device performed as designed. It use, without modification, in the next investigation is highly recommended. Since the measuring phase of the experiment was anticipated to be the most difficult, it is felt that the design and manufacture of a perfectly operating device to do this was a major accomplishment. It now remains for this equipment to be incorporated in a system to load and heat properly, and the desired results may be obtained.

e. In final conclusion: The research into the literature, the discussions with the thesis advisor, designing and building the equipment, and running the experiments were most enjoyable and informative. Much work remains to be done in this field and it is hoped that the foregoing will be some small aid to whoever shall continue in this endeavor.

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